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► **To cite this version:**

A. Medvedeva, F. Clairet, C. Bottereau, R. Marcille, S. Hacquin, et al.. Development of the synthetic diagnostic for the ultra-fast swept reflectometer: ASDEX Upgrade team 4 , EUROfusion MST1 team 8. 14th International reflectometry workshop, IAEA, May 2019, Lausanne, Switzerland. cea-02288900

**HAL Id: cea-02288900**

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Submitted on 16 Sep 2019

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# Development of the synthetic diagnostic for the ultra-fast swept reflectometer

A. Medvedeva<sup>1</sup>, F. Clairet<sup>1</sup>, C. Bottereau<sup>1</sup>, R. Marcille<sup>2</sup>, S. Hacquin<sup>1,3</sup>, G. D. Conway<sup>4</sup>, U. Stroth<sup>4,5</sup>, S. Heuraux<sup>6</sup>, G. Dif-Pradalier<sup>1</sup>, D. Molina<sup>1</sup>, A. Silva<sup>7</sup>, ASDEX Upgrade team<sup>4</sup>, EUROfusion MST1 team<sup>8</sup>

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<sup>8</sup>For a list of members, see H.Meyer et al, Nucl. Fusion 57 102014 (2017)



This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

## 1. Motivation:

Role of turbulence in plasma confinement

## 2. Ultra-fast swept reflectometer

Diagnostic capabilities for turbulence measurements

## 3. Synthetic diagnostic

Project progress

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Plasma in a tokamak must be:

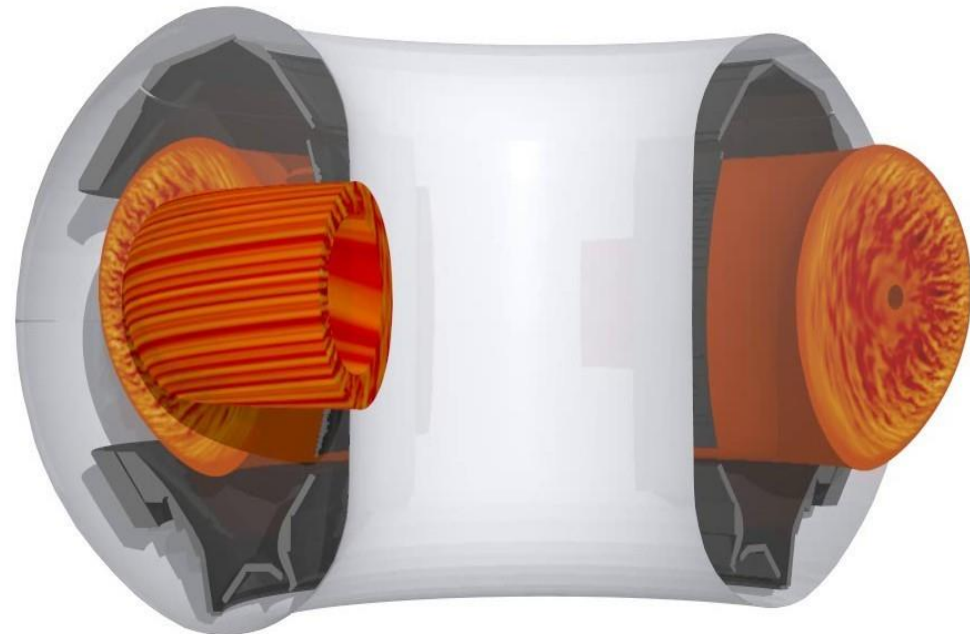
- hot and dense at the core
- cool at the edge

} → gradients → turbulence

Turbulence should be understood, predicted and **reduced** for a better confinement

**Objective:**

Investigate turbulence during confinement changes

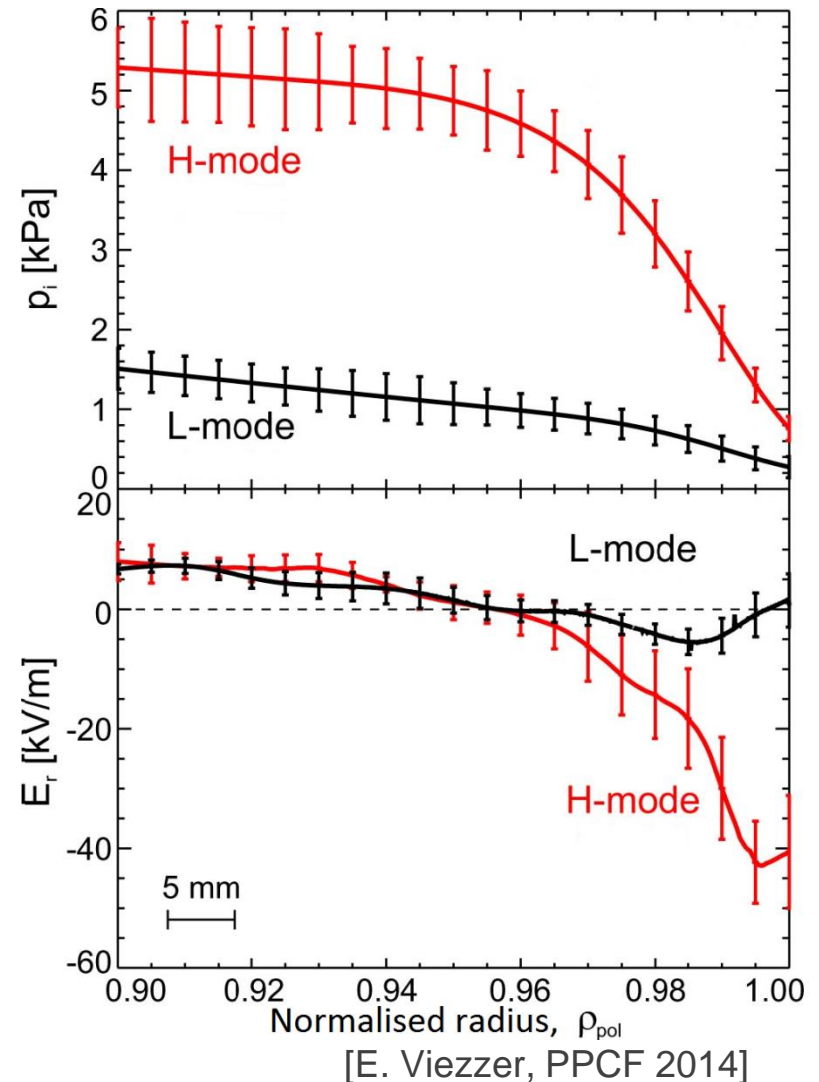
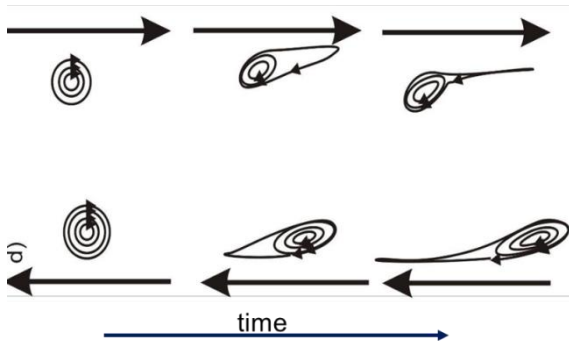


$\delta T$  in the ASDEX Upgrade tokamak with GENE code [genecode.org]

low confinement (L-mode) → high confinement (**H-mode**)

[F. Wagner, PRL1982]

- Transport of heat and particles **reduced**
- Drift velocity  $\vec{v}_{E \times B} = \frac{\vec{E} \times \vec{B}}{B^2} \propto E_r$
- Increase of the radial electric field creates  **$E \times B$  shear flow**
- Shear flow suppresses **turbulence**



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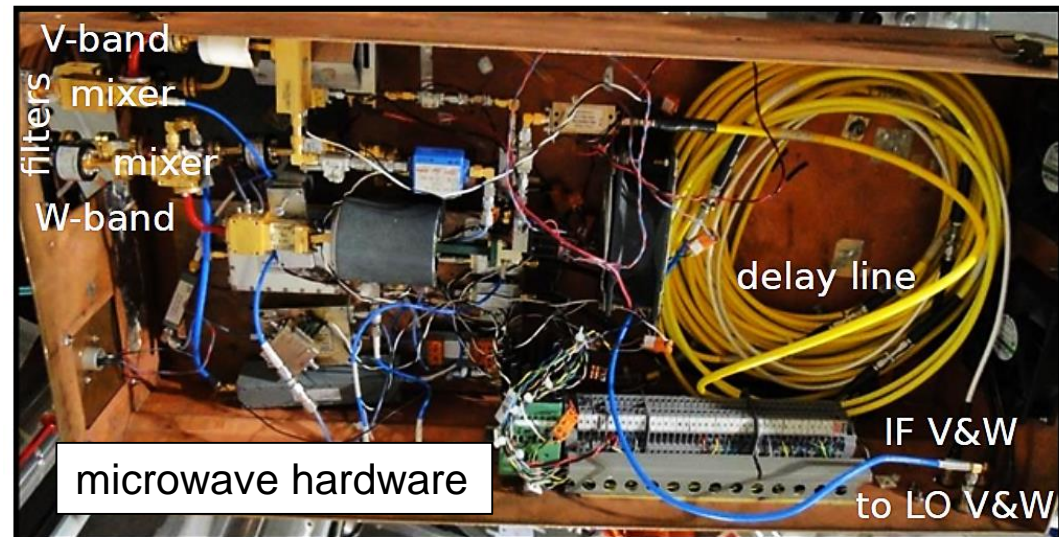
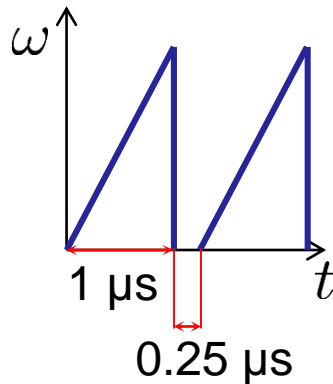
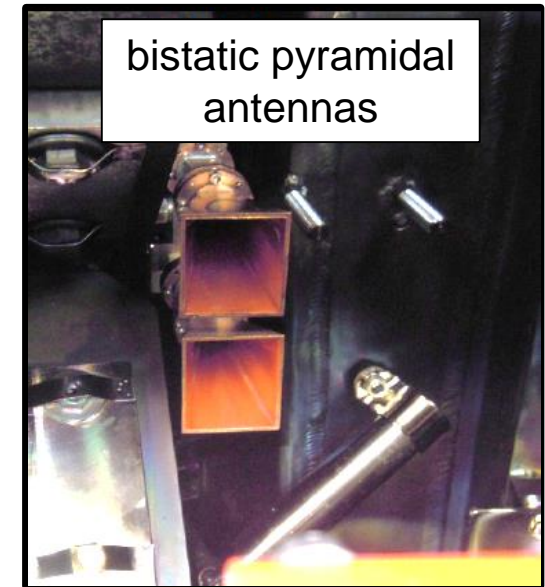
## 2. Ultra-fast swept reflectometer

Diagnostic capabilities for turbulence measurements

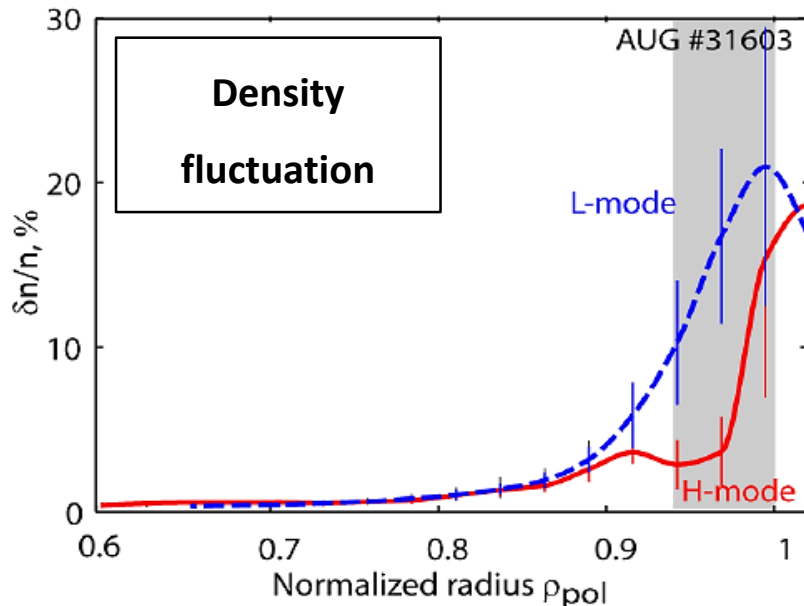
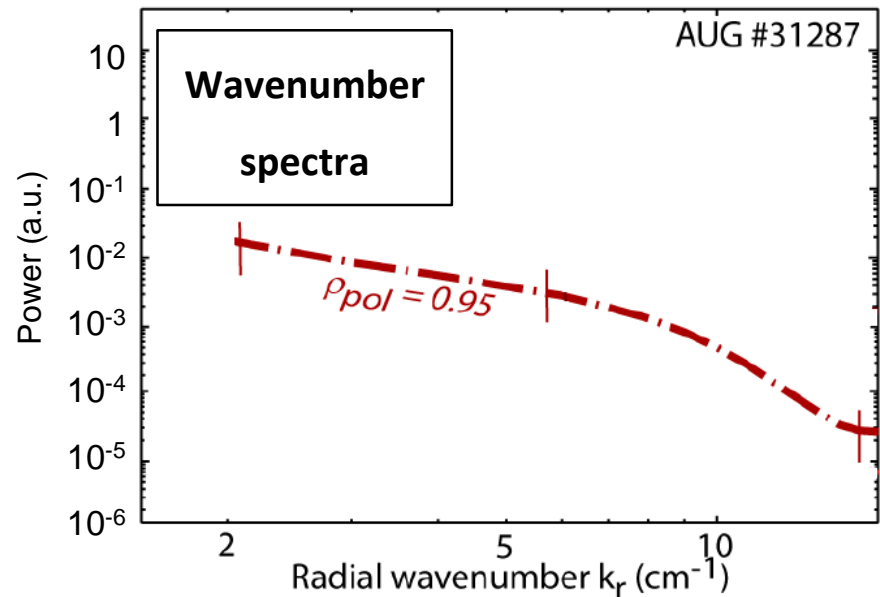
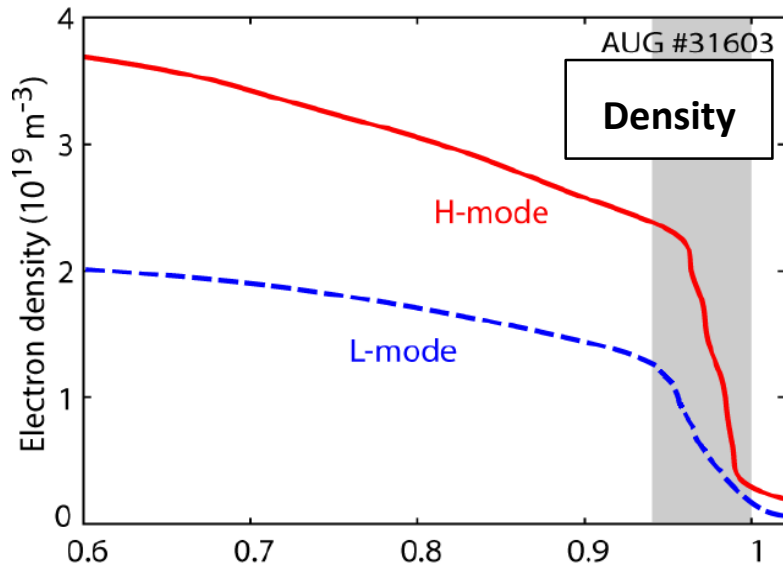
## 3. Synthetic diagnostic

Project progress

- **UFSR** developed at CEA for Tore Supra and WEST tokamaks, transferred to ASDEX Upgrade (2013–2016) supported by EUROfusion
- 50–102 GHz X-mode
- Acquisition 2Gs/s
- Sweep time 1  $\mu\text{s}$   
[F. Clairet, RSI 2017]







- Density profiles with  $1 \mu\text{s}$  resolution
- 1D wave propagation simulation  $\rightarrow$  radial wavenumber spectra
- Density fluctuation (turbulence level)
- Frequency spectra up to 400 kHz
- Correlation length and time
- **2D effects to be considered**

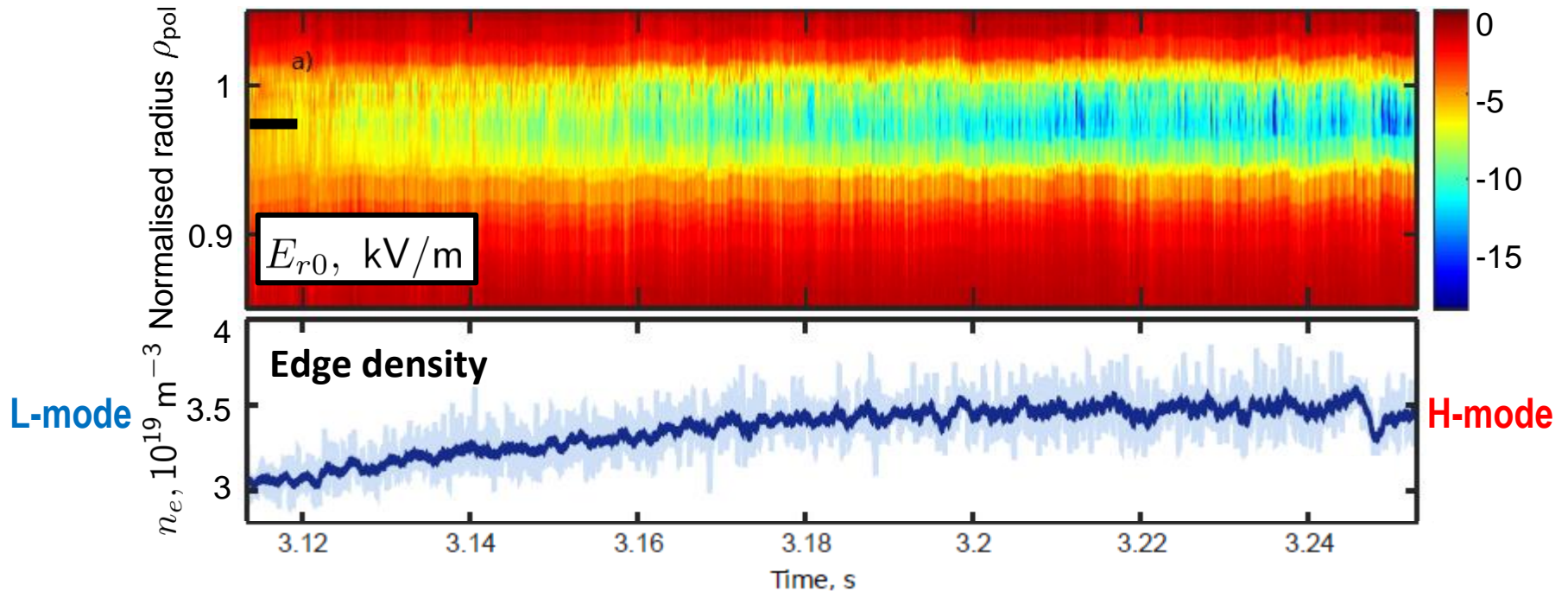
[A. Medvedeva, IRW 2015]

Proxy for radial electric field:

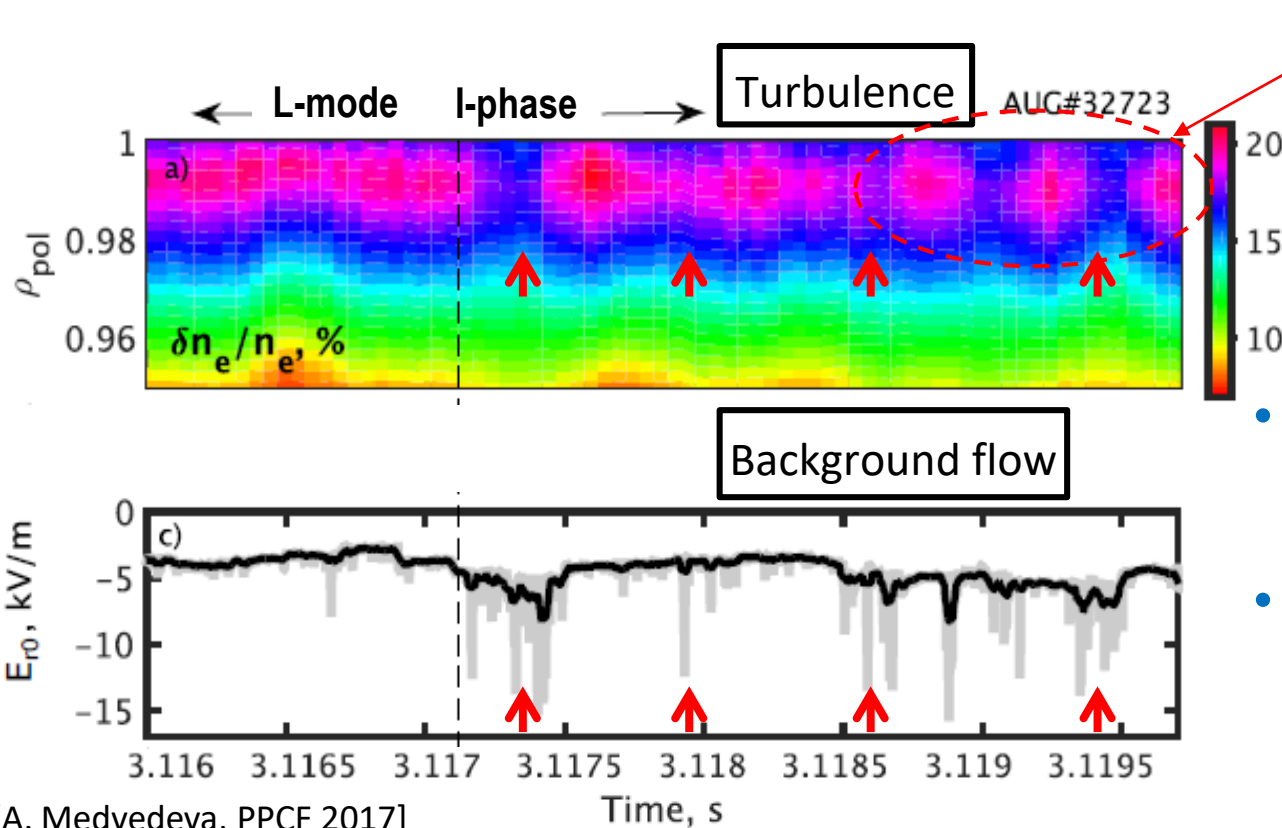
UFSR

$$E_r \approx \frac{\nabla p_e}{en_e} = T_e \frac{\nabla n_e}{en_e} + \frac{\nabla T_e}{e} = E_{r0}$$

[F. L. Hinton, RMP 1976]



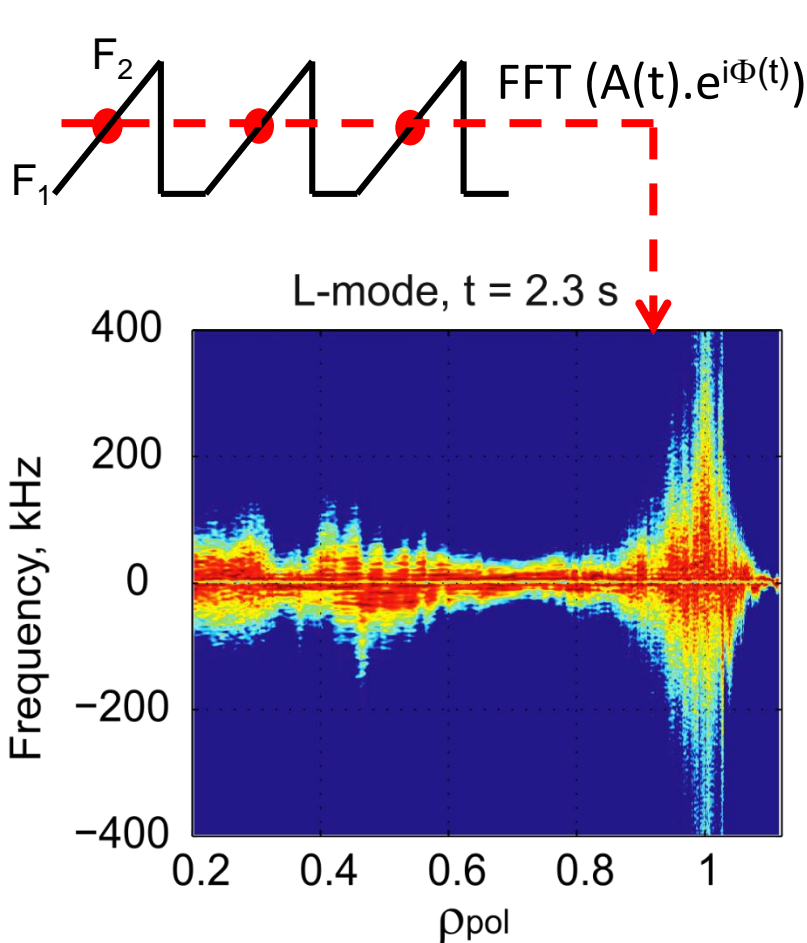
$E_{r0}$  minimum (at  $\rho_{pol} = 0.98$ ) deepens during I-phase from  $-5$  to  $-20$  kV/m



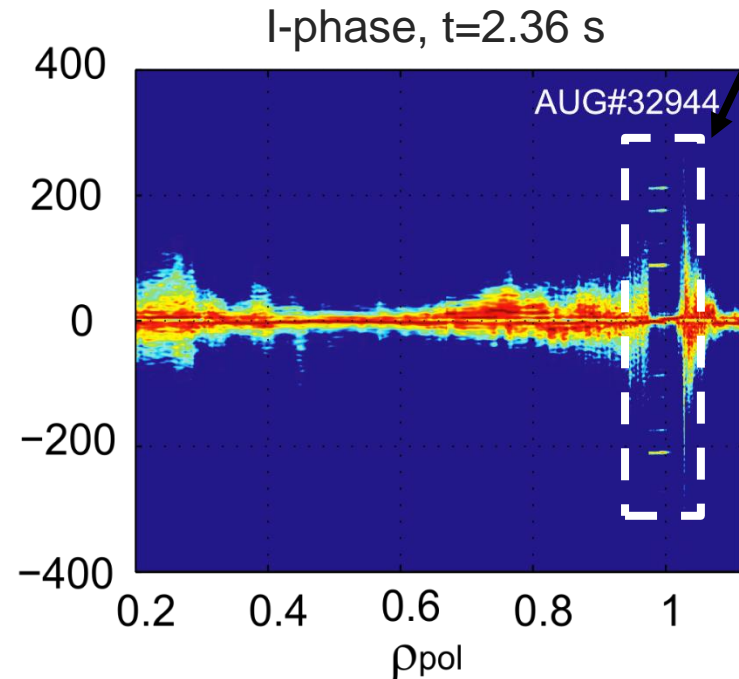
regular oscillations in established I-phase

- Deep negative values of  $E_{r0}$  appear between the turbulence bursts
- Crash of  $E_{r0}$  happens together with the turbulence increase

- Established I-phase might be explained by edge instabilities causing a fast relaxation of pressure (turbulence and flow in phase)
- Edge coherent modes appear in the pedestal region and might play a role



Edge coherent modes  
[A. Medvedeva, 45th EPS 2018, PPCF accepted]



In the pedestal region  $0.95 < \rho_{pol} < 1$  the fluctuation amplitude decreases, the spectra become narrower during the I-phase and in H-mode due to the radial electric field shear

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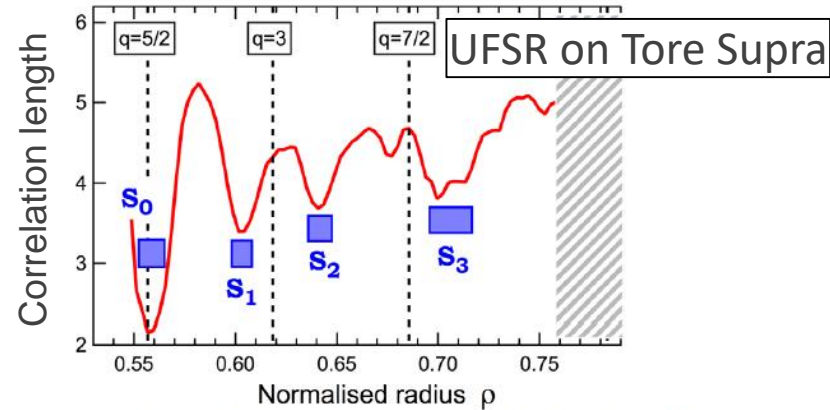
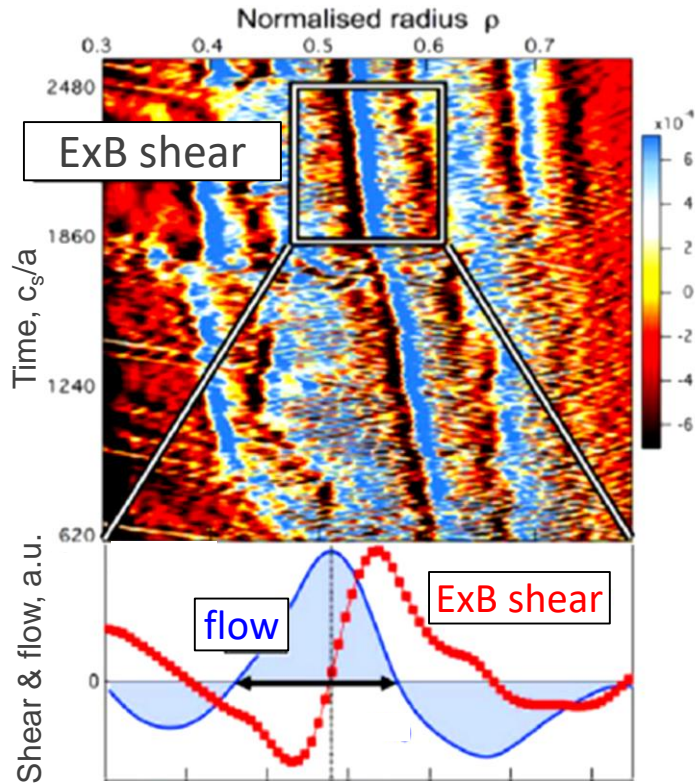
Diagnostic capabilities for turbulence measurements

## 3. Synthetic diagnostic

Project objectives and progress

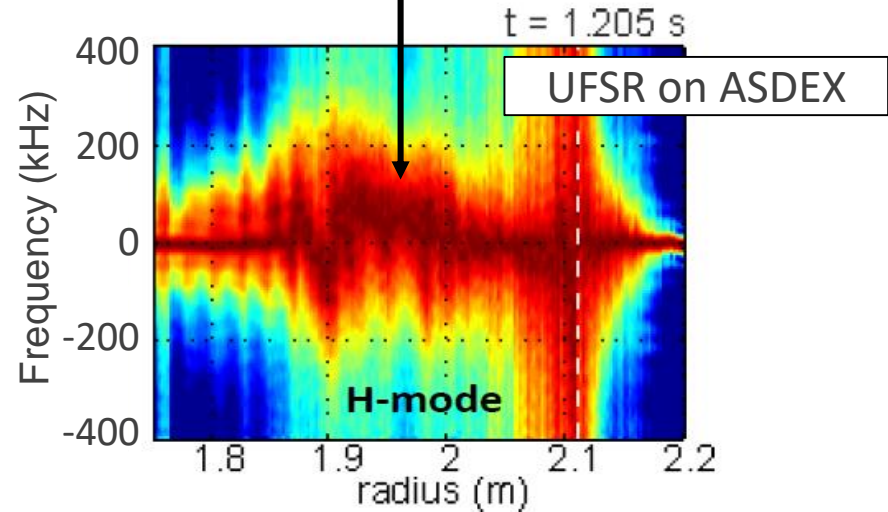


Spontaneous organisation of a set of regularly spaced weak transport barriers:  
ExB staircase predicted by GYSELA

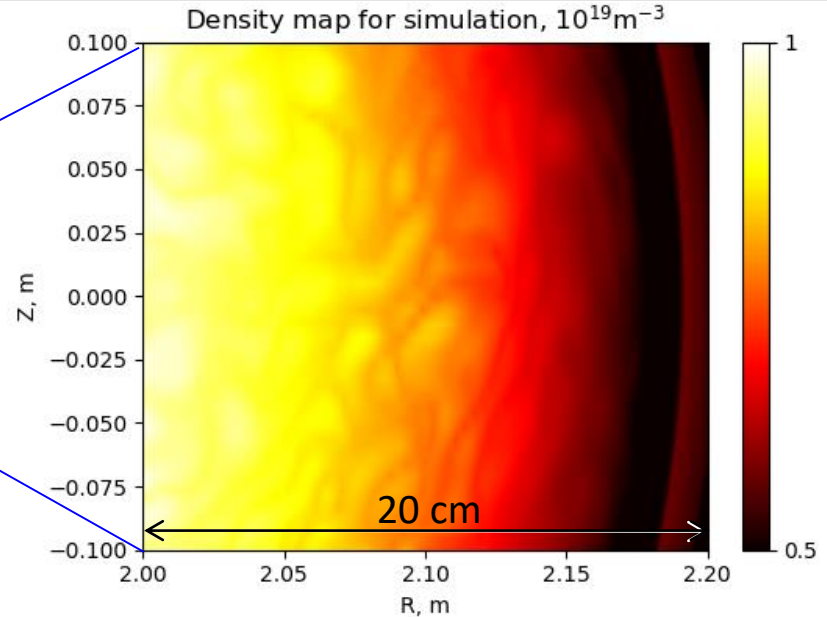
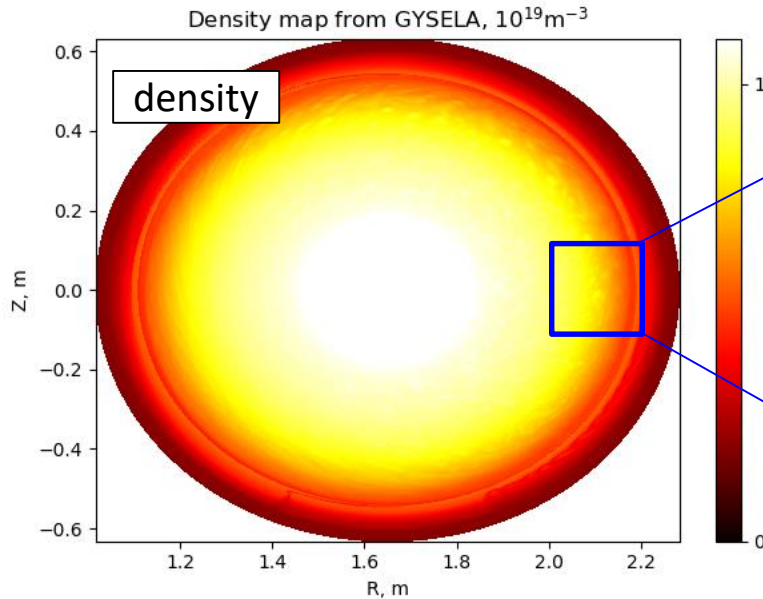


[G. Dif-Pradalier et al., PRL 2015, NF 2017]  
[G. Hornung, NF 2017]

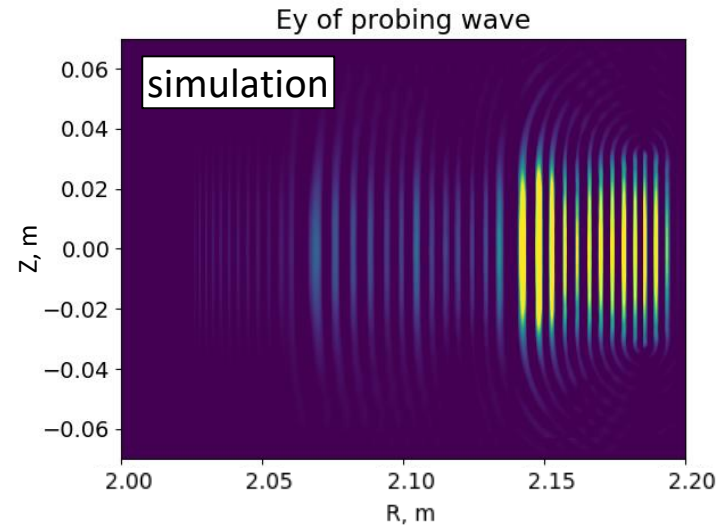
Staircase structure? Flow dynamics?

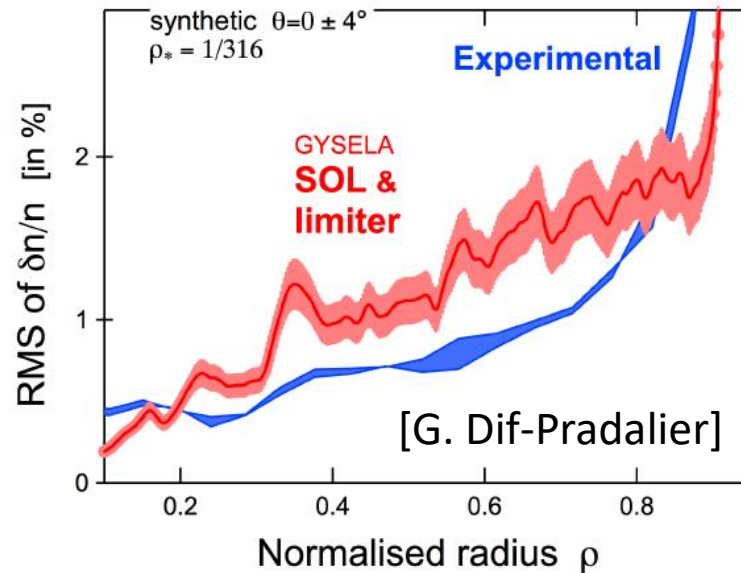
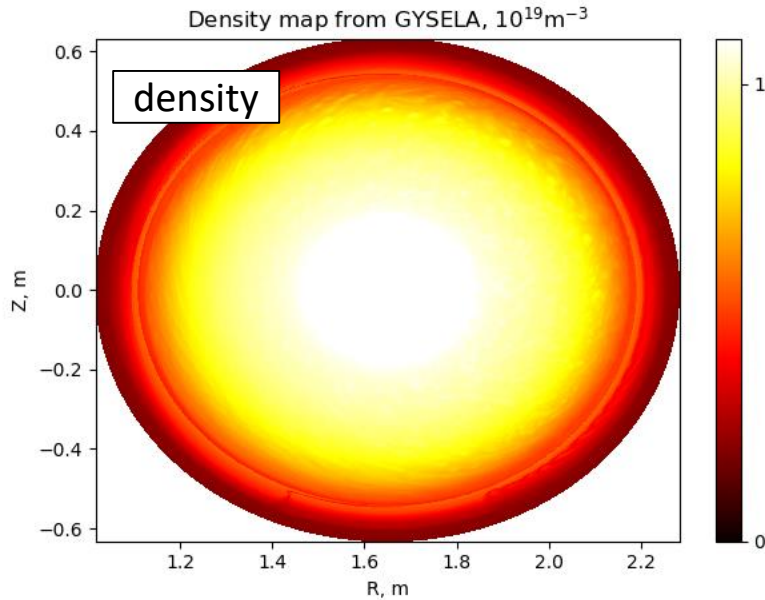


Project at the crossroads between theory, simulation and experiments



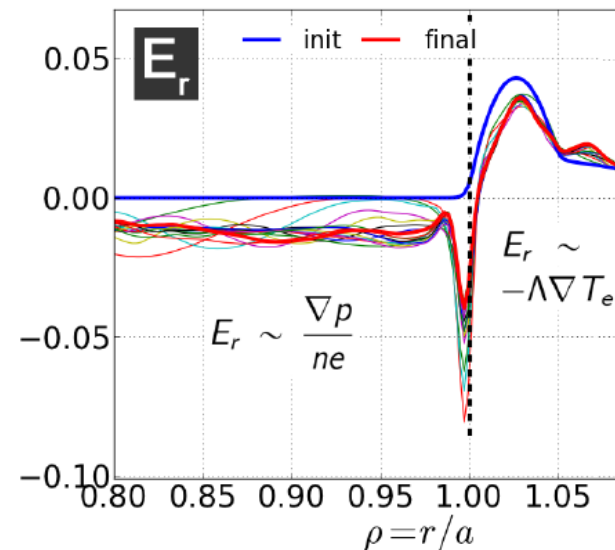
- Turbulence map simulated with gyrokinetic code
- ↓
- Finite Difference Time Domain 2D code for wave propagation
- ↓
- Reproduce frequency and wavenumber spectra, correlation length and time
- ↓
- Compare with turbulence code





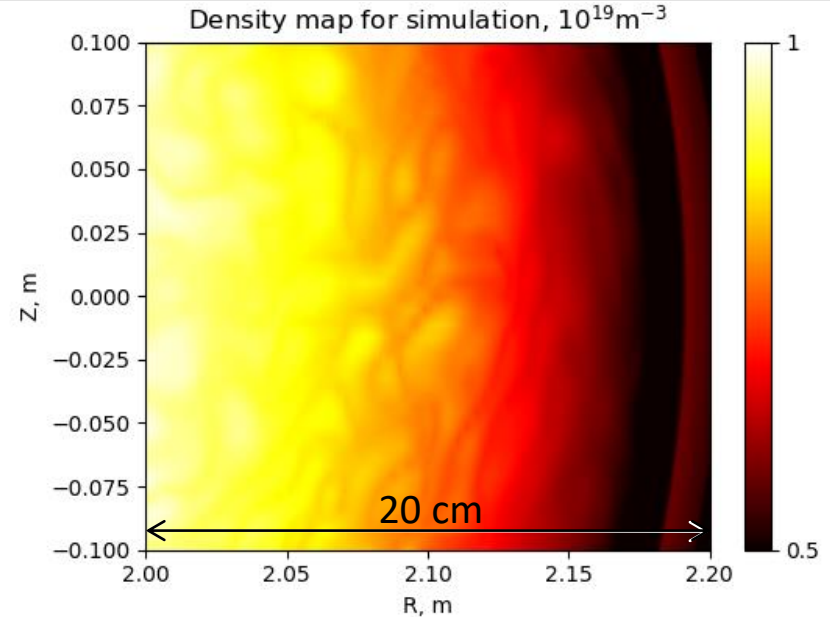
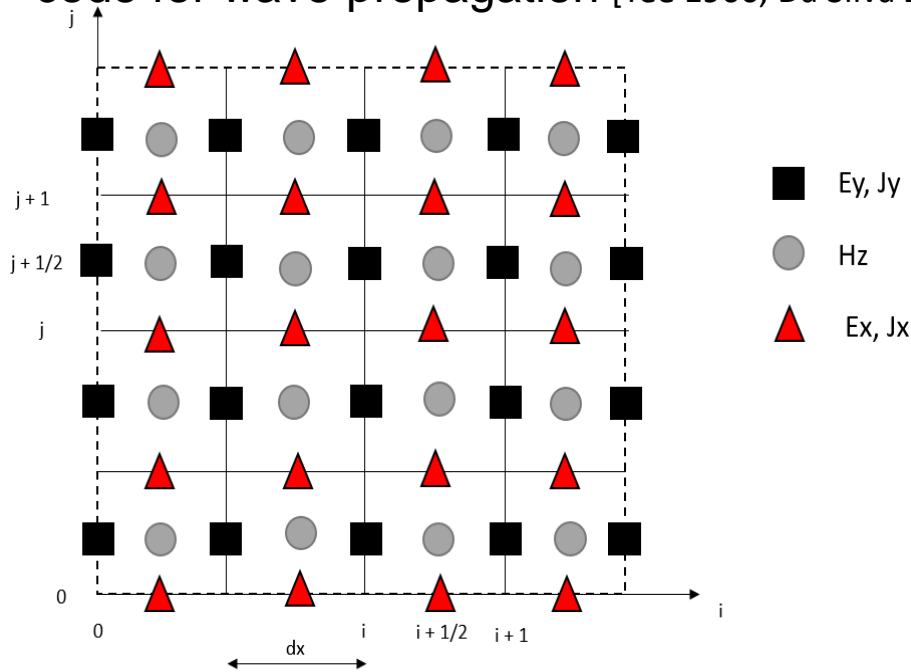
Low collisional plasma  $\rightarrow$  gyrokinetic description

- flux-driven  $\rightarrow$  mimic experiments
- self-consistent interplay btw core, edge & simplified SOL model
- global description: kinetic ions & adiabatic or kinetic trapped electrons
- self-organised  $E_r$  well





- Finite Difference Time Domain 2D full wave code for wave propagation [Yee 1966, Da Silva 2014]



$$dt = \frac{1}{40f_0} = 5 \cdot 10^{-13} \text{ s}, dx = 2c dt$$

Soft source:  $H_z(kdx, y, ndt) = H_z(kdx, y, (n - 1)dt) + e^{j\omega(ndt)} e^{-\frac{(y-y_0)^2}{\sigma^2}} \frac{A_0}{\sqrt{\epsilon_0 \mu_0}}$

Measured signal:  $E_y^n(x_s, y_s) = A_0^* e^{j\omega_0 ndt} + a_1^* e^{j(\omega_0 ndt - \phi)}$

Calculation speed (Python+C): 1000 x 1000 x 5000 points 10min for  $F_0$

$\begin{matrix} x & y & t \end{matrix}$

Sweep:  $\omega_0 \rightarrow \omega = \omega_0 + v_\omega t$

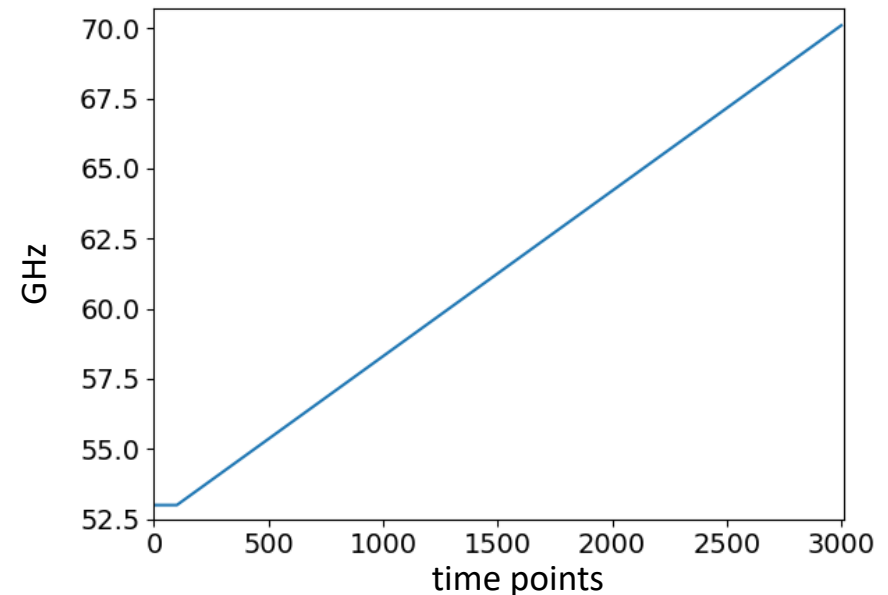
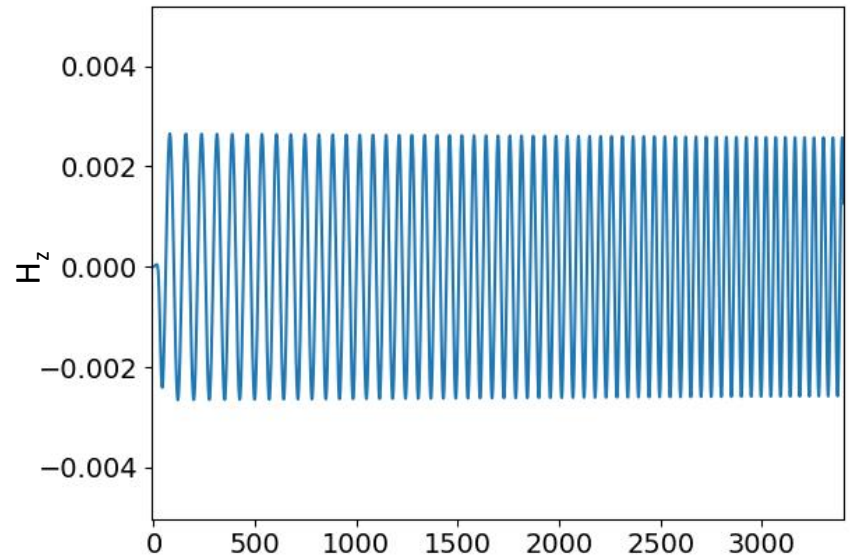
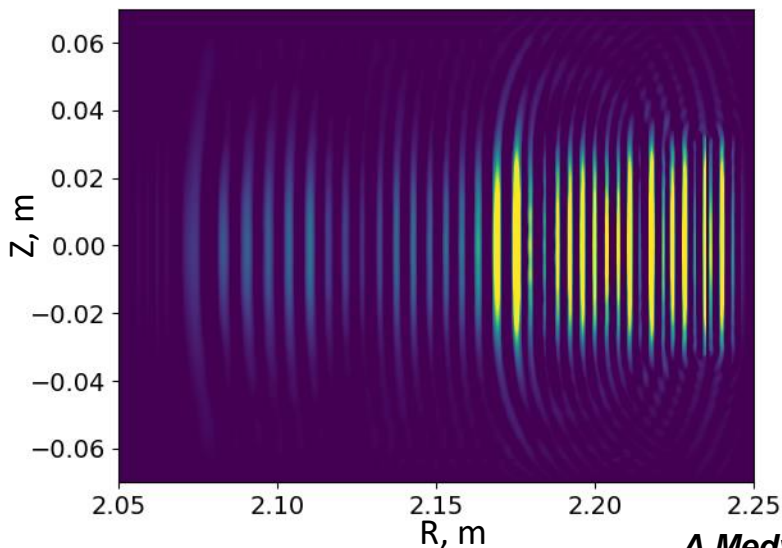
Source:  $e^{i(\omega_0 t + v_\omega t^2 + \Delta\varphi(t))}$

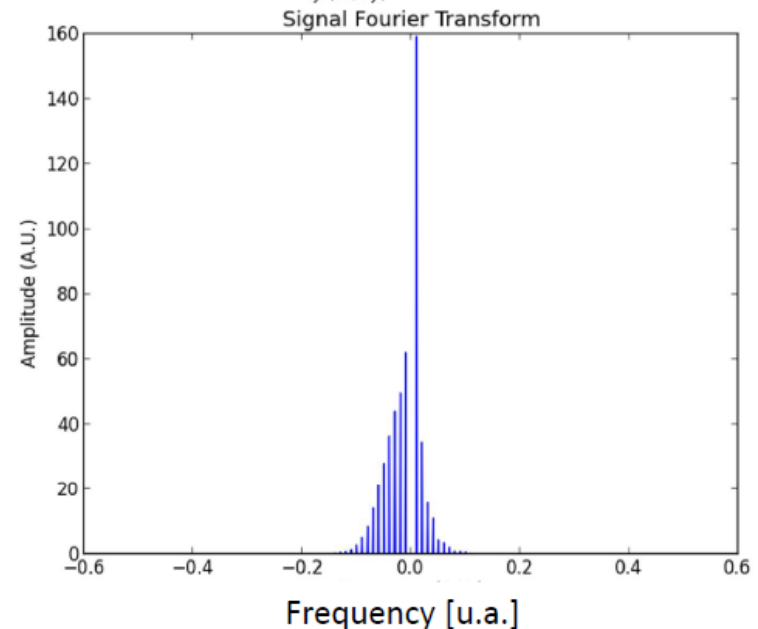
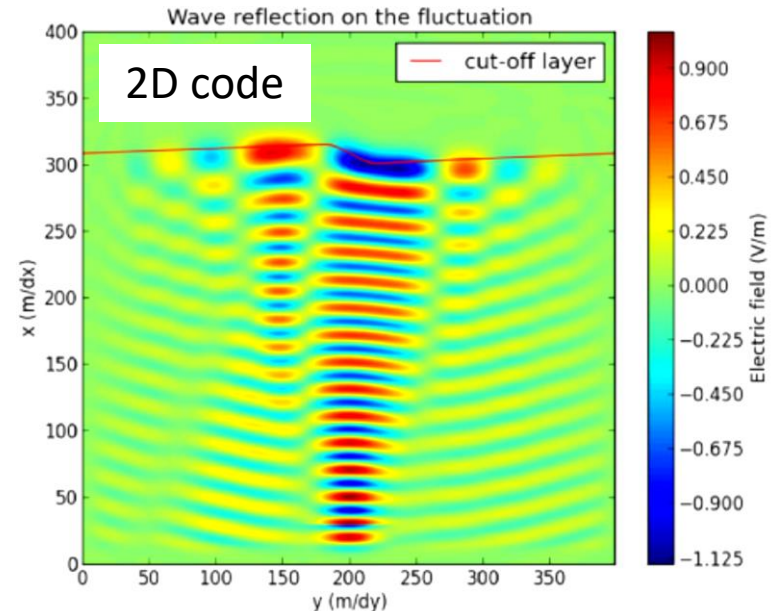
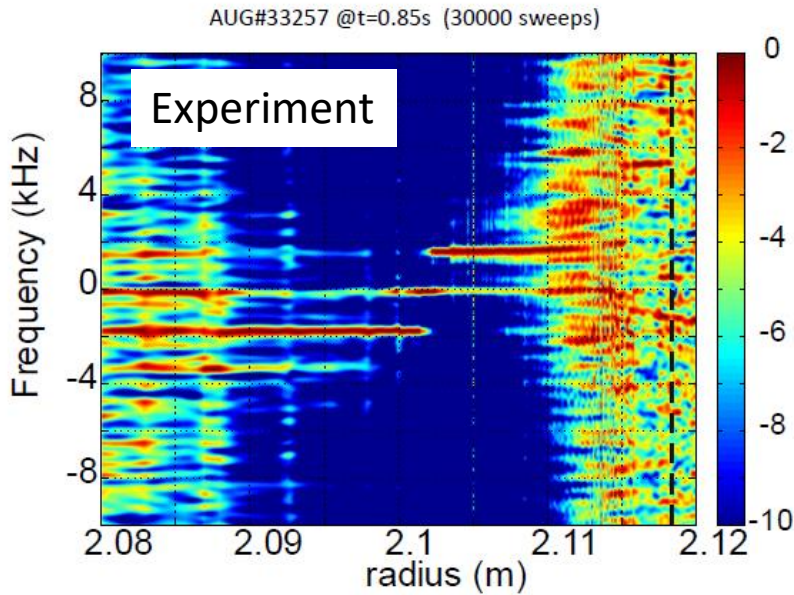
+ Mimic real reflectometer

- Optimised calculation speed
- 1  $\mu\text{s}$  sweep 2 000 000 points  $\rightarrow$  70 hours
- 0.01  $\mu\text{s}$  sweep 20 000 points  $\rightarrow$  1 hour

$$F_{beat} \approx 400 \text{ MHz} \rightarrow 40 \text{ GHz}$$

- Difficulties of signal extraction





Sign inversion of the spectra asymmetry during I-phase can be explained by a sawtooth-like cutoff layer

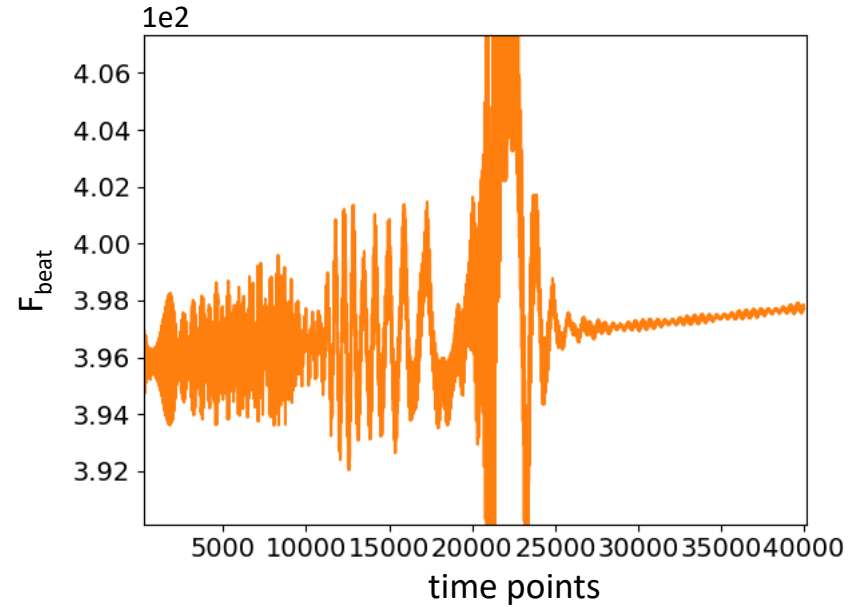
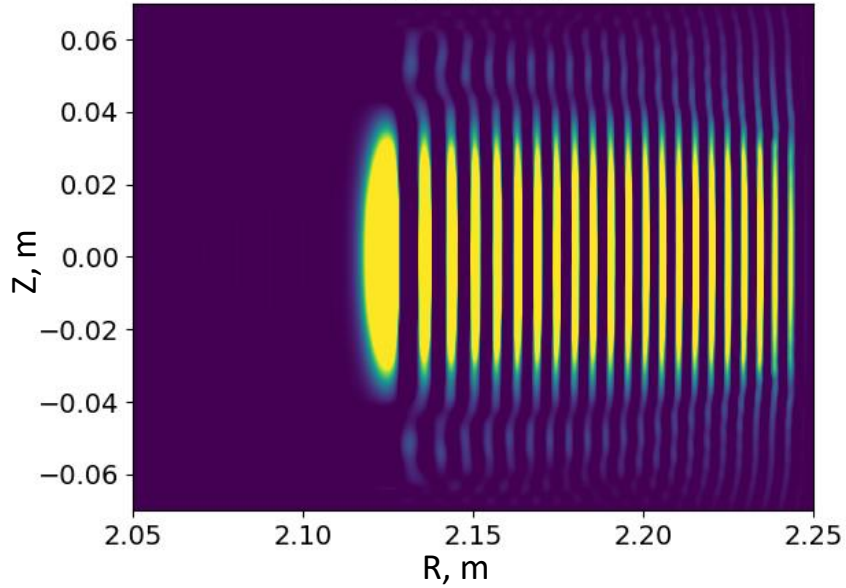
Further application:  
 modes' size, flow detection, turbulence level and wavenumber spectra, correlation analysis

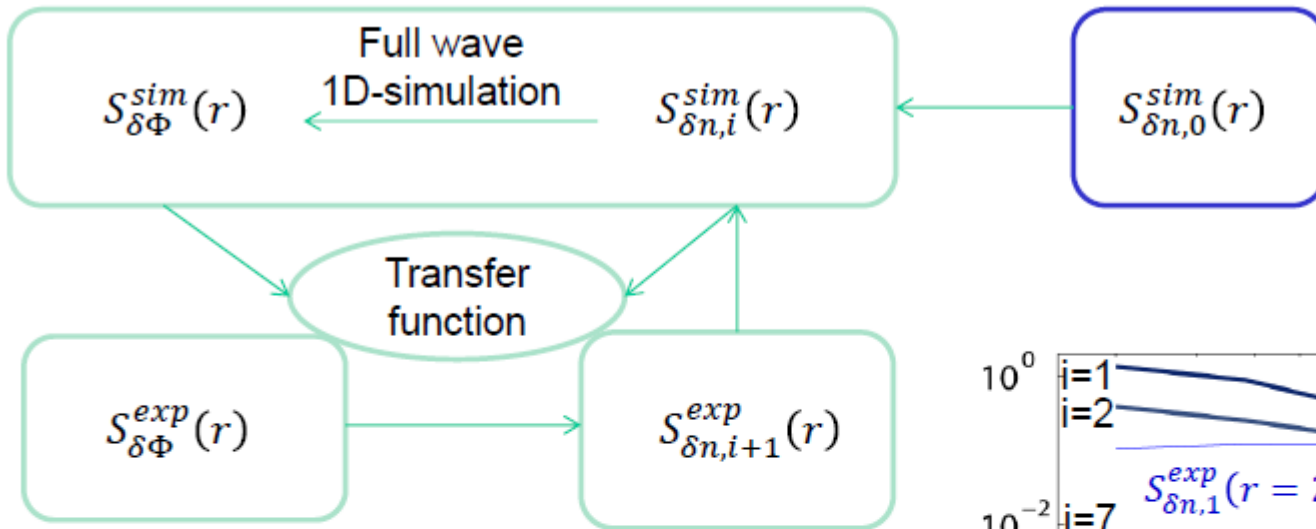
2018

- Create 2D full wave code
- Couple with GYSELA turbulence maps
- Parallel calculation for (F,t) – 10 min each
- Optimise calculation speed by sweeping of frequency
- Integrate 2D code to the loop method of wavenumber/turbulence level analysis
- Add functions for correlation analysis
- Reproduce spectra for various turbulence scenarios for ASDEX Upgrade and WEST data, compare with GYSELA and GENE

- First studies of the electron density and density fluctuations dynamics during L-H transitions in ASDEX Upgrade have been performed with a time resolution of 1  $\mu$ s using 1D wave propagation simulation.
- 2D full wave code is developed for interpretation of ultra-fast swept reflectometer data and coupled with GYSELA and GENE turbulence simulations.
- Synthetic diagnostic is being optimised for further data analysis.

Ey of probing wave

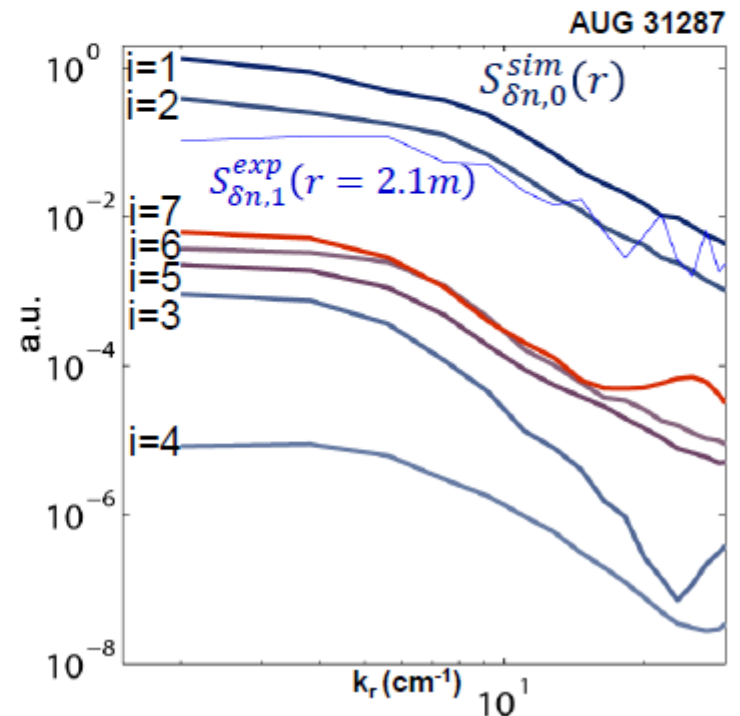




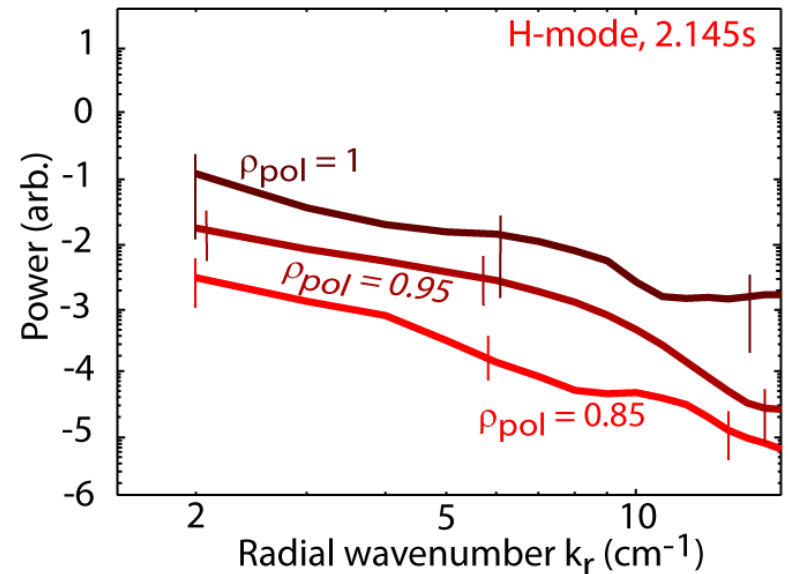
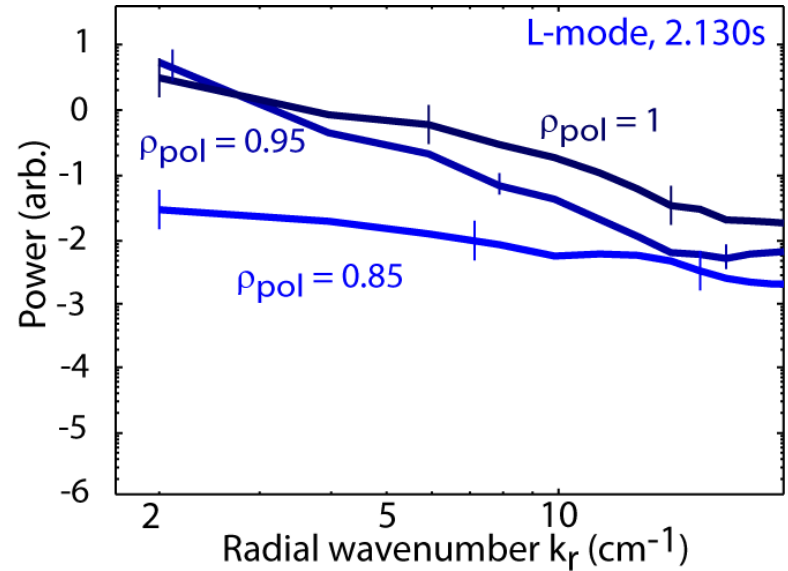
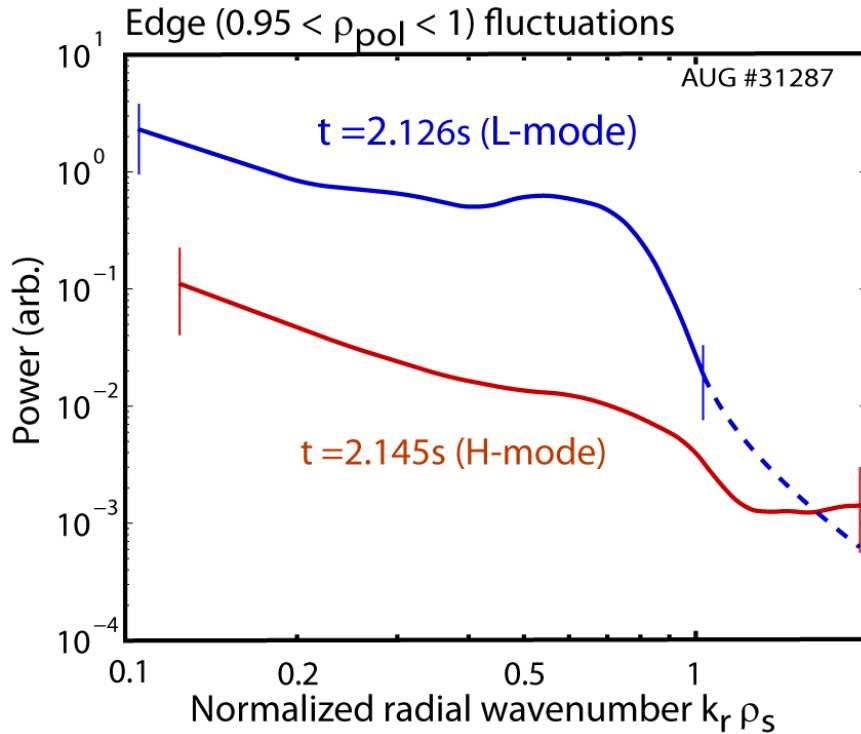
Signal phase fluctuations are induced by density fluctuations:  $S_{\delta n}(k) = T(k) \cdot S_{\delta\Phi}(k)$

Density fluctuations level:

$$\left(\frac{\delta n}{n}\right)^2 = \frac{1}{k_{max} - k_{min}} \int_{k_{min}}^{k_{max}} S_{\delta n}(k) dk$$







- Turbulence level falls towards core
- After L-H transition density fluctuations with small  $k_r$  are suppressed in the pedestal region

$$\rho_s = \frac{\sqrt{T_e/m_i}}{\Omega_{ci}}$$

ion-sound Larmor radius